NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4056

LOADS IMPLICATIONS OF GUST-ALLEVIATION SYSTEMS

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SUMMARY

A review is presented of the factors affecting gust loads and the methods or devices which reduce these loads. Aerodynamic devices which reduce the lift-curve slope include spoiler-deflector controls, for which some data are presented in the Mach number range from 0.4 to 1.1. Systems are also considered in which a sensing device is used to operate gust-alleviation controls. Two basically different types of sensing devices are possible, the load-sensing type and the angle-of-attack-sensing type. These devices are compared and their limitations discussed. Some preliminary flight measurements of wing-root bending moment due to turbulence are presented for a gust-alleviation system installed in a small twin-engine transport airplane. This system increased the wing-root bending moments as compared with those of the basic airplane. This increase resulted from the fact that the system as tested was adjusted to reduce acceleration and, as a result, overcompensated for the wing-root bending moments due to gusts. Some flight measurements of the effects of a yaw damper on the tail loads of a bomber airplane are also presented.

INTRODUCTION

Gust alleviation has been of continued interest to almost every group in aviation since its inception, but it has not been incorporated in production airplanes. Apparently the reason for the lack of use of gust alleviation is that detailed analyses of promising devices either pose problems insoluble at a given stage in aircraft development or result in practical disadvantages that seem to outweigh the potential benefits. Systems have been studied by various organizations with the objectives of providing improved riding comfort, increased safety due to load reductions, reduced structural weight, and more stable gun platforms.

Inasmuch as the various systems are perennially proposed as means of improving aircraft, a need for a summary of the methods available for gust alleviation and the problems associated with these methods is apparent. The present report considers the loads implications of gust-alleviating methods.

SYMBOLS

c	wing chord
C_{L_α}	lift-curve slope
q	dynamic pressure
U	gust velocity
V	true airspeed
ΔC_D	drag-coefficient increment
M	Mach number
α	angle of attack
V_S	velocity at stall
V_C	cruising speed
V_{MAX}	maximum speed

DISCUSSION

The factors affecting gust loads are shown in table 1. The first factor is the direct load due to the gust. As indicated by the formula, this load is proportional to the lift-curve slope C_{L_α}, the dynamic pressure q, and the change in angle of attack due to the gust, U/V, where U is the gust velocity and V is the true airspeed. This load may therefore be reduced by reducing C_{L_α} or by reducing q. The second factor is the airplane motion due to gusts or due to controls. The airplane motion is dependent on the basic airplane stability, and may also be influenced by the operation of controls manually or by an autopilot. The third factor to be considered is the action of special controls to offset the gust load directly. This category would include the relieving effects due to wing bending, the use of hinged surfaces or wings, and finally the use of special gust-alleviating controls, such as wing flaps, operated by a servomechanism.

Effect of Spoiler-Deflector Control

Aerodynamic devices which reduce the lift-curve slope include the use of sweep or reduced aspect ratio, the effects of which are well known, and the use of chordwise slots which, in effect, reduce the aspect ratio. Another device for reducing the lift-curve slope is the spoiler-deflector control (ref. 1). The effects of this device as a function of Mach number on a swept wing are shown in figure 1. This figure shows the percent of the basic wing load produced by the wing with a spoiler-deflector control covering 18 percent of the span. The increment in drag coefficient is also shown. These data are taken from reference 2. The spoiler height above the wing was 0.025c and the deflector projection below the wing was 0.15c. In this case, the reason for the short span of the spoiler-deflector control was to locate it inboard of the aileron and outboard of the horizontal tail. This device provides a large increase in drag as well as a reduction in lift-curve slope. For this reason, this control might be useful for slowing an airplane down when rough air is encountered but it would not be desirable for continuous use in high-speed flight. Tests on specific configurations have shown that this control may be located so as to minimize longitudinal trim changes. Location of the spoiler-deflector control ahead of an aileron, however, has been found to reduce greatly the aileron effectiveness, as might be expected. Possibly, the spoiler-deflector control could be operated in conjunction with the aileron to overcome this difficulty.

Effect of Sensor and Servo System Operating Special Controls

In systems which use a sensing device to detect the gusts and to operate gust-alleviation controls, two basically different types of sensing devices are possible: one, the load-sensing type such as strain gages or an accelerometer, and the other, the angle-of-attack-sensing type. The effects of these devices differ in several important respects. First, as shown in figure 2, these sensing devices exhibit different trends of effectiveness as a function of airspeed. The gust envelope for a typical transport airplane is also shown in this figure. With the load-sensing type of gust alleviation the percent alleviation increases with increasing speed, whereas with the angle-of-attack-sensing type the percent alleviation tends to remain constant. Thus, if the two systems are designed to have the same effectiveness at a given speed, the load-sensing type will show greater effectiveness at higher speeds. These results apply only if the system gain is held constant as might occur with the use of some simple types of aerodynamically operated gust alleviators. If a servo system is used, of course, it is possible to vary the gain of the system as a function of speed and thereby change the effects of speed from those shown.

The second difference between the two systems is concerned with the different nature of the effects which limit the maximum alleviation obtainable. The usual limitation in the case of the load-sensing system is the occurrence of a high-frequency instability. Figure 3 shows the percent load experienced with a load-sensing system as a function of the relative gain. A relative gain of 1 on this scale represents a condition in which, for example, a load increment corresponding to 1 g on the sensor will operate the controls to produce a load increment of -1 g on the airplane. Very high gains are required to obtain a large percent of alleviation. A load-sensing system, however, is a typical closed-loop system, for which high gains are likely to result in instability. Analog-computer studies for certain typical cases have shown that reduction in load below 50 percent of the unalleviated case resulted in an oscillatory response and that these oscillations became unstable at a higher gain as shown.

With the angle-of-attack-sensing system, this type of instability is much less likely to be encountered because this arrangement is much more nearly an open-loop system, that is, operation of the angle-of-attack sensor causes deflection of the alleviation controls but operation of the alleviation controls has only a minor effect on the indications of the angle-of-attack sensor. For this reason, the limitation is less on the amount of gain which may be employed, and systems are designed usually so that the effect of a uniform gust is completely counteracted by the alleviation controls. With this type of system the limits on the load reductions obtainable result primarily from the fact that sensing the gust at one point does not give a representative indication of the average angle of attack across the wing span. Unpublished theoretical studies have shown that the effect of nonuniform gust velocity across the span for the angle-of-attack-sensing system is a function of the ratio of the wing span to the scale of turbulence. Because of the large scale of atmospheric turbulence, values of alleviation as high as 80 percent may be obtained with a single sensor located ahead of the nose which operates the controls with no lag. The addition of a suitable filter to the output of the sensor which reduces the response to high-frequency gusts further improves the alleviation theoretically attainable. Such a filter may also be desirable in order to reduce the effects of structural feedback, which might cause the system to reinforce structural modes of oscillation if the system response were not attenuated at high frequencies.

Flight Tests of Gust-Alleviation System

Installed in Airplane

A flight investigation has been made of a gust-alleviation system installed in a small twin-engine transport airplane. Some preliminary results of this study have been reported previously (refs. 3 and 4). This system was designed primarily for the improvement of passenger comfort. The system uses an angle-of-attack vane to operate wing flaps through a servo system. The reduction in acceleration obtained with this system is shown in figure 4. The relative values of normal acceleration as a function of frequency, obtained with the basic airplane and the gust-alleviated airplane for comparable conditions of turbulence, and the effect of the system on pitching velocity are shown. The relative values plotted in this figure are proportional to the square root of the power spectral density of the response and show the correct relative values as well as the variation of the response with frequency. The normal acceleration for the alleviated airplane was reduced to 30 or 40 percent of that for the basic airplane in the frequency range from 0 to 2 cyles per second. The pitching velocity, which was small for the basic airplane, was further reduced for the alleviated case.

Extensive strain-gage measurements have been made to determine the effect of this system on the structural loads. These data have not been completely evaluated at this time. The effect of the system on wing-root bending moment is shown in figure 5. The wing-root bending moment is actually increased by the gust-alleviation system. The explanation of this increase is indicated by the insert on the figure which shows the change in span load distribution for basic and alleviated airplanes due to a small positive increment of angle of attack. In the alleviated case, the flaps on the wing are deflected up on the outboard sections and down near the root. This arrangement provides downwash conditions at the tail which minimize pitching moments due to the gusts. The resultant lift due to this combination is about zero, but because the tip sections are much more effective in producing bending moment, the result is a negative bending moment due to an up gust. The magnitude of this negative bending moment is actually greater for a given gust than the positive bending moment on the basic airplane.

These results apply only so long as the system is operating in its linear range. At a gust velocity of about 10 feet per second, the flaps reach their stops. For greater up-gust velocities, the bending moments would increase in the positive direction as on the basic airplane. Thus, for a gust velocity of 20 feet per second, the bending moment would be expected to come back to about zero, and for higher gust velocities would again become positive. This sytem is therefore one which serves to improve passenger comfort in the frequently encountered small gust velocities, but which reduces the structural loads due to severe gusts. No flight data are available, however, to show the characteristics of the system in severe turbulence. The system increased the magnitude and frequency of tail loads as well as the stresses in minor structural components such as the rear spar, the wing flaps, and so forth. This result indicates that fatigue loads would be a more serious problem for the gust-alleviated airplane.

Effect of Yaw Damper on Vertical-Tail Loads

Some measurements have been made to determine the effect of a yaw damper on the vertical-tail loads experienced by a bomber airplane in rough air at various altitudes. These results are shown in figure 6, which presents the probability of exceeding a given value of vertical-tail spar strain with the yaw damper on and off at two altitudes, 35,000 feet and 5,000 feet. The yaw damper reduces the magnitude of loads considerably in the high-altitude case. The damping of the Dutch roll motion of the airplane under these conditions is low so that a large resonance at the Dutch roll frequency is obtained. The effect of the yaw damper is primarily to reduce this amplification of load due to the Dutch roll motion. At low altitude where the damping of the airplane is better, the gains due to the yaw damper are small.

Some studies have been made to determine the feasibility of reducing the loads on the wings by use of the normal elevator control. The results are similar to those obtained in the lateral case; that is, if the airplane has very low damping in pitch the loads may be reduced through elimination of the resonant peak of the short-period mode (ref. 5). However, any attempt to reduce the direct effect of the gust on the lift of the surfaces by heading the airplane into the gusts requires large pitching motions of the airplane.

CONCLUDING REMARKS

A brief review has been given of the basic methods of gust alleviation, and some results obtained in flight tests of a gust-alleviation system have been presented. A system designed for improvement of passenger comfort did not reduce structural stresses while operating in its linear range. The system would be expected to reduce the wing loads due to severe gusts, but loads in the tail and other structural components were increased.

Langley Aeronautical Laboratory,
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Langley Field, Va., March 5, 1957.

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TABLE I

FACTORS AFFECTING GUST LOADS

Δ LOAD = SUM OF

1- DIRECT LOAD DUE TO GUST- $\left(C_{L_\alpha} q \frac{U}{V}\right)$

(A) C_{L_α}

(B) q

2- AIRPLANE MOTION DUE TO GUST OR CONTROLS

(A) BASIC AIRPLANE STABILITY

(B) OPERATION OF CONTROLS MANUALLY OR BY AUTOPILOT

3- ACTION OF SPECIAL CONTROL TO OFFSET LOAD

(A) WING FLEXIBILITY

(B) HINGED SURFACES

(C) SENSOR AND SERVO SYSTEM OPERATING SPECIAL CONTROLS

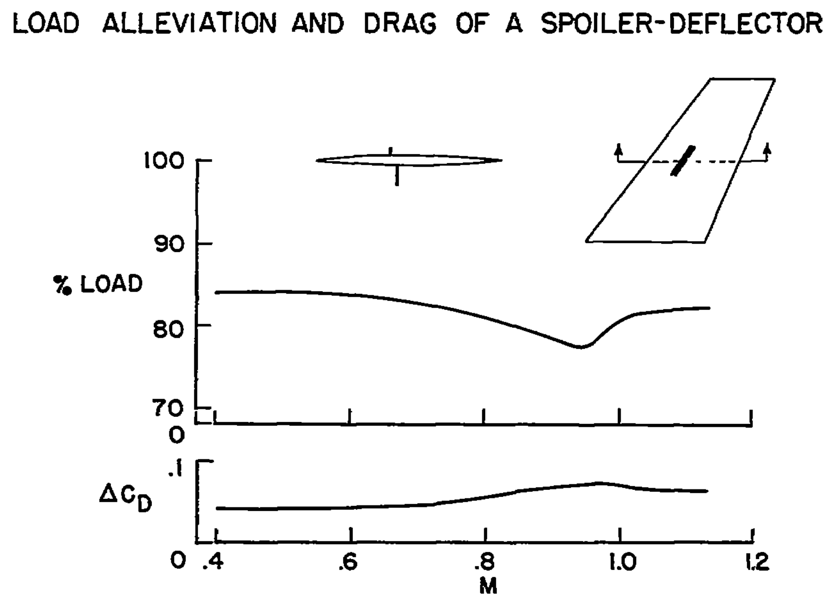

Figure 1

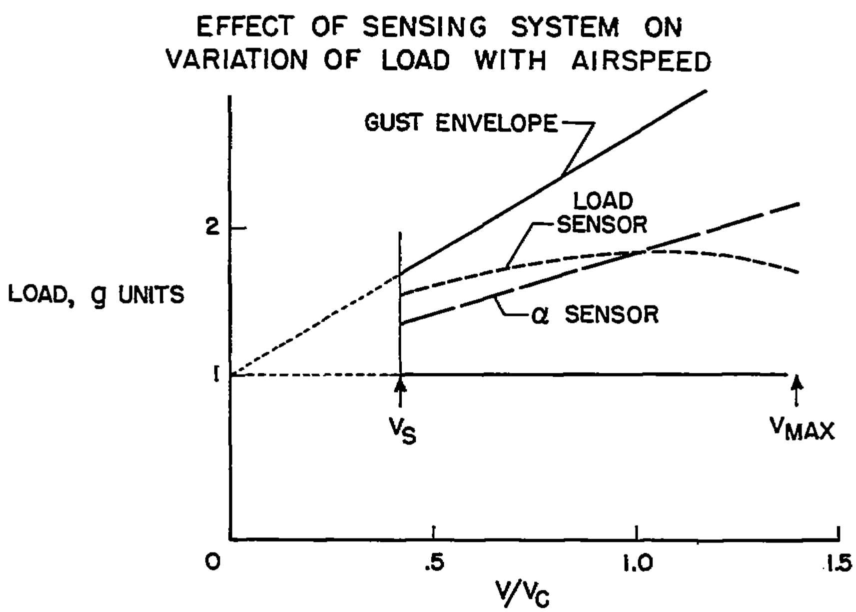

Figure 2

LOAD REDUCTION WITH LOAD-SENSING SYSTEM

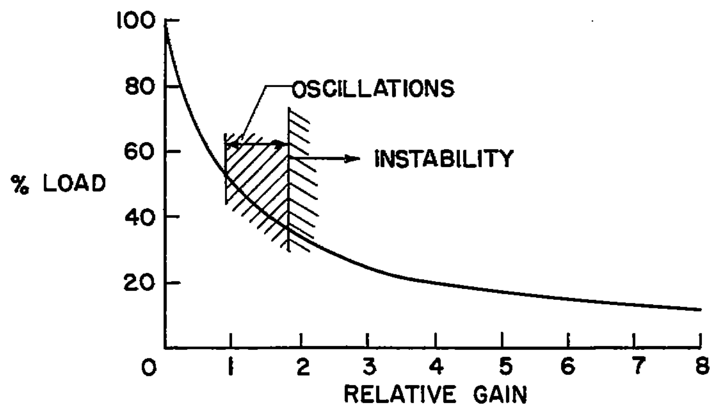

Figure 3

EFFECT OF GUST-ALLEVIATION SYSTEM ON AIRPLANE MOTIONS

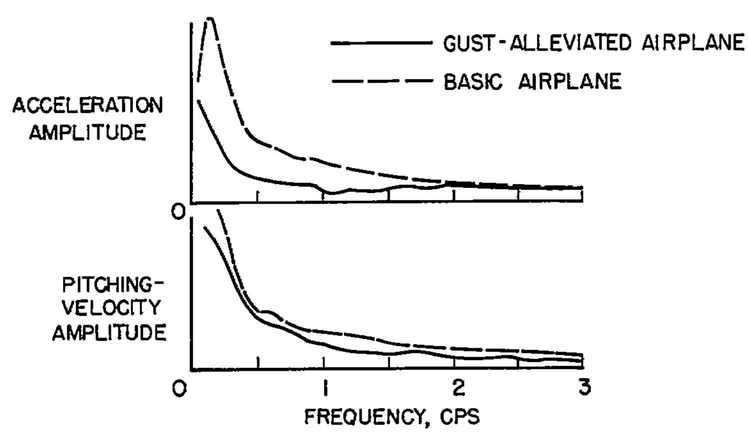

Figure 4

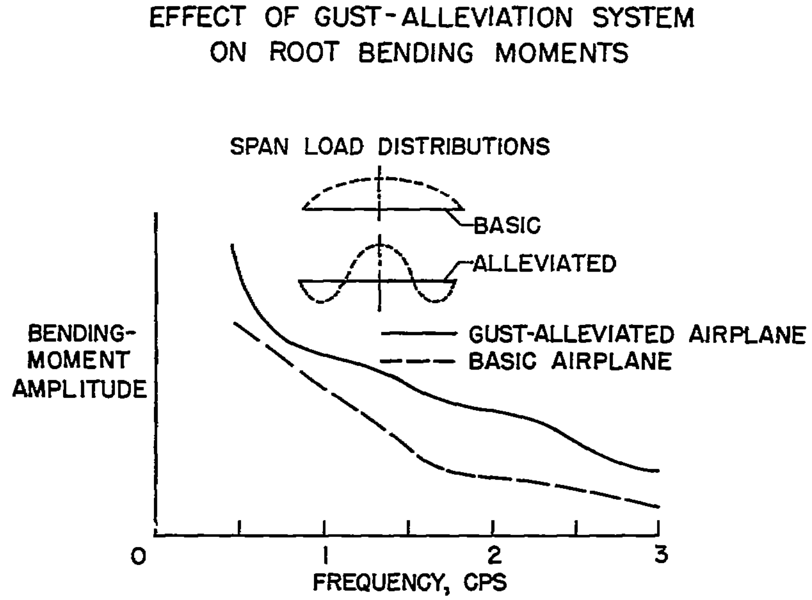

Figure 5

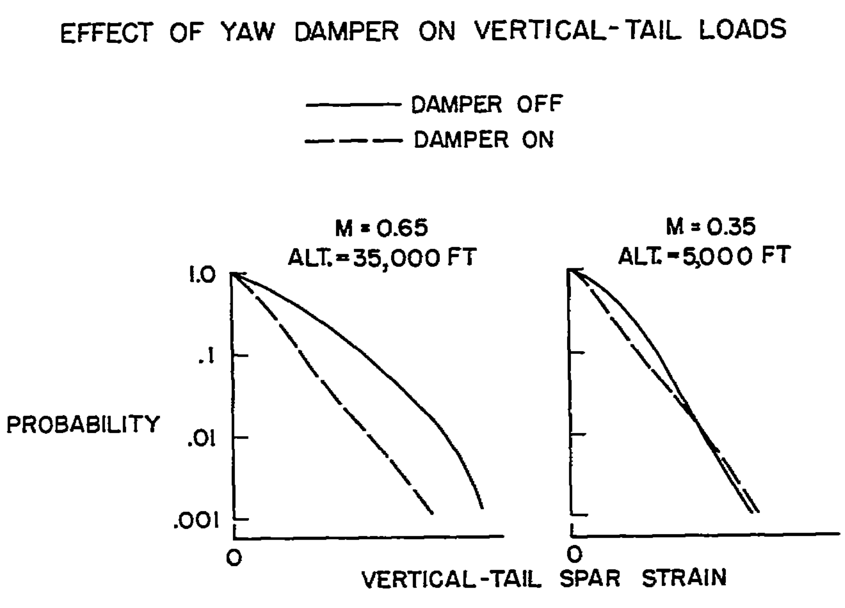

Figure 6